Characterization Methods for Shape and Length Nanoscale Metrology

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Projects

Nanotechnology Standardization: Form of Nano structure

- *The goal was to collaborate on the development and standardization of nanoscale probe characterizers.*
- *As part of this collaboration, we evaluated the use of the comb characterizer for critical dimension AFM (CD-AFM) probes.*

Nanotechnology Standardization: Size of Nano Structure

- *The goal of the project was to collaborate in developing traceable physical standards for height and lateral dimensions.*
- *This will serve as part of a body of data in support of standardizing these samples for AFM vertical scale calibration.*

ITRS Lithography Metrology Uncertainty Specifications for Select Parameters

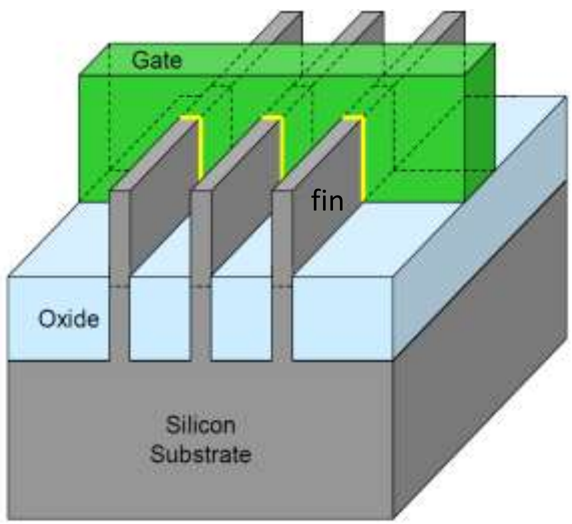
One of the motivations of this work is the need to meet industry specifications for nanoscale length measurements. The international technology roadmap for semiconductors (ITRS) uncertainty specification for fin height and gate overhang are currently either in yellow or red, indicating that values are not currently being met. The work is also applicable to a wide range of nanoscale characterization.

Gate and Fin Sidewall Angle (°)

Year	Specif.
2016	0.3
2020	0.3
2025	0.3

Fin Height (nm)

Year	Specif.
2016	0.5
2020	0.3
2025	0.2



(Diagram of tri-gate finFETs)

Fin Top Corner Rounding Radius (nm)

Year	Specif.
2016	0.3
2020	0.2
2025	0.1

Gate Overhang (nm) (gate height above fin)

Year	Specif.
2016	0.5
2020	0.5
2025	0.3

finFET: fin based field Effect Transistors

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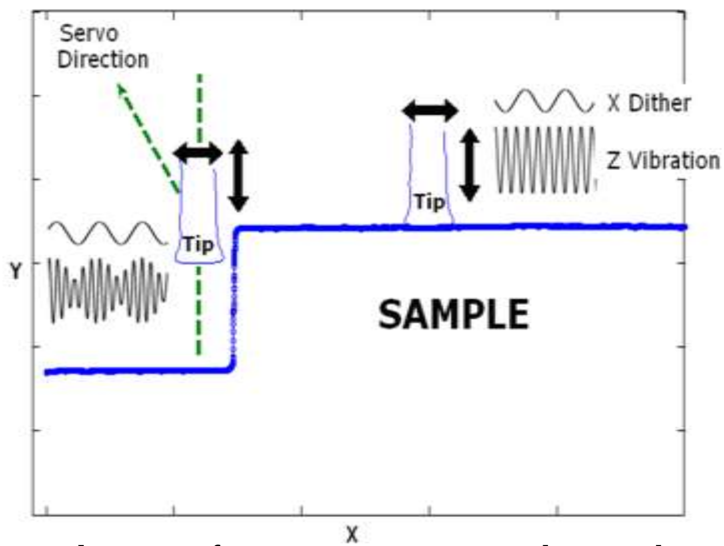
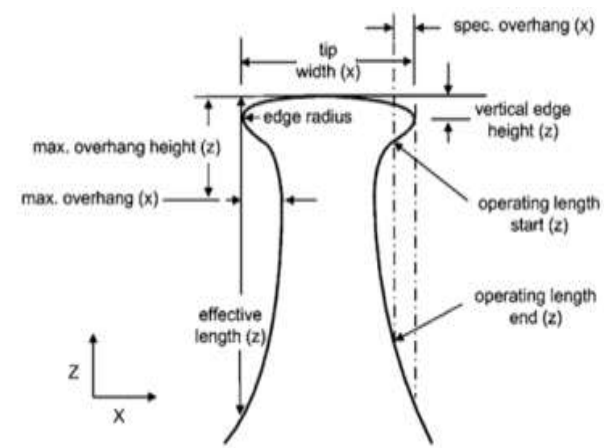
3D –AFM Application

The CD-AFM uses flared tips, sub-resonant lateral dithering of the tip in addition to the near-resonant vertical oscillation of the cantilever, and a bidirectional servo and feedback system. This combination allows the imaging of vertical and even reentrant sidewalls, which are crucial to quantifying 3D features. To obtain shape information, some of the tip parameters listed below must be known.



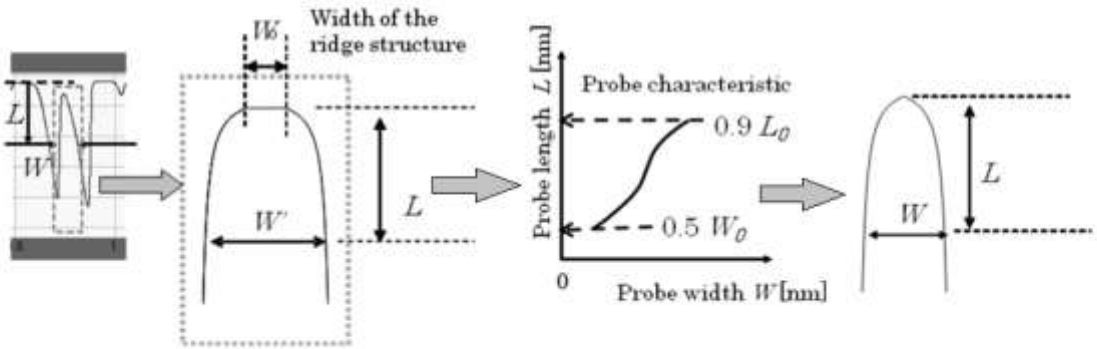
Schematic diagram of CD-AFM operation. The tip vibrates in the *Z* direction and dithers in the lateral direction. The tip tracks both the vertical and lateral surfaces by adjusting the servo direction when a change in slope is detected by the sensor.



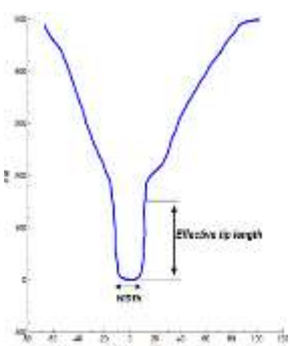
Flared 3D-AFM tip shape parameters

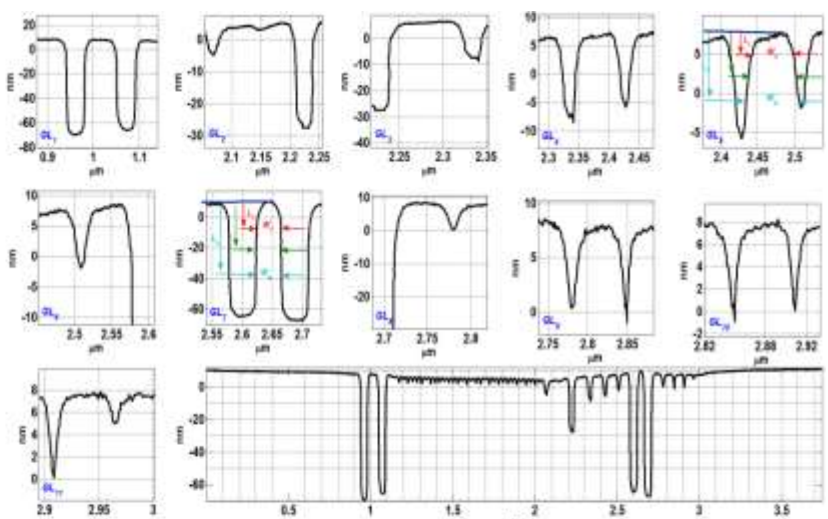
Image from G. Dahlen et al. J. Vac. Sci. Technol. B 23, 2297 (2005);

Probe Shape Characteristic– Cylindrical CD-AFM Tip



Probe shape characteristic determination using the narrow ride structure.

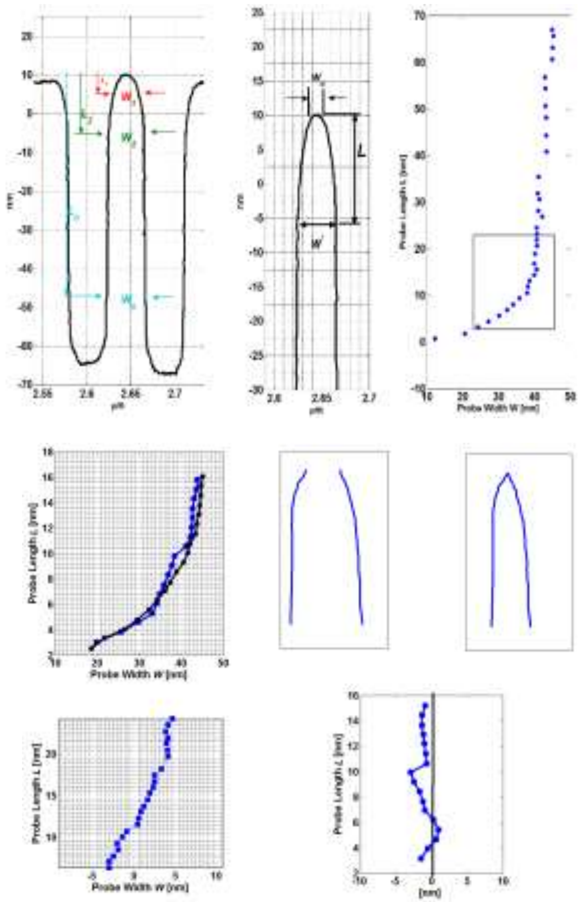


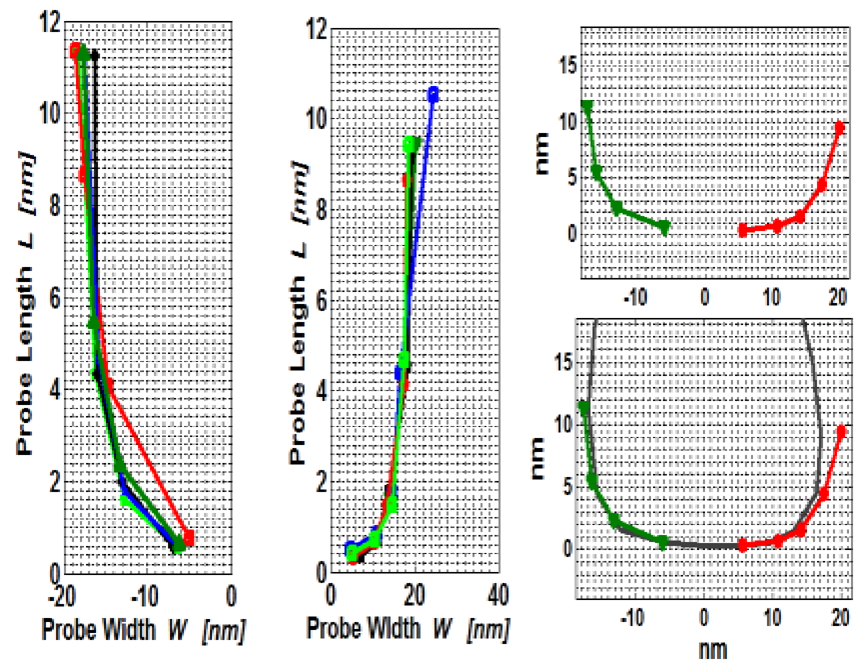


This example shows probe shape estimation using cylindrical tips. The technique can also be applied to flared tips, but does not yield tip reentrant parameters.

The features include the size of the tip!

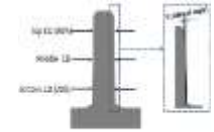
Probe Shape Characteristic– Cylindrical and Flared CD-AFM Tip





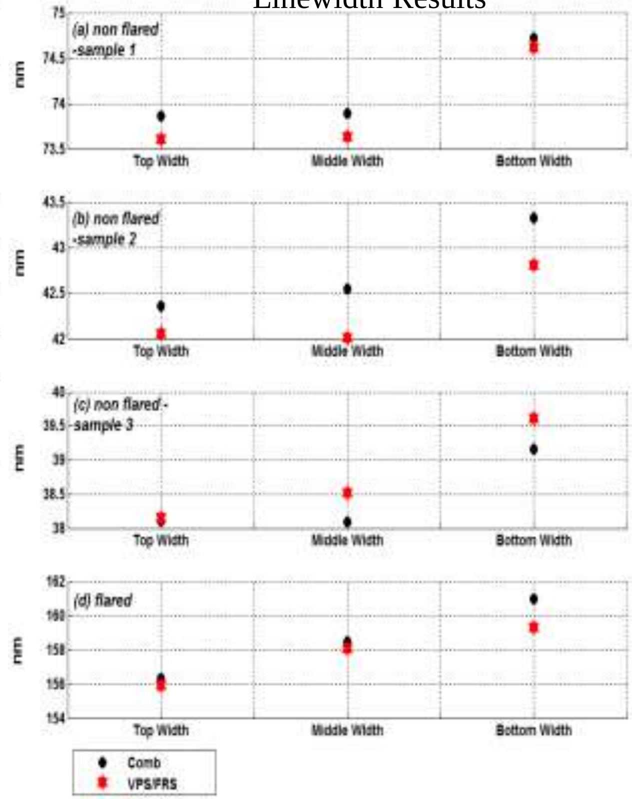
For flared CD tips, the width and edge height can be determined.

Comparison with Other Techniques



Characterizer	Important Metrology Aspects						
	Intrinsic Accuracy		Undercut	Measurement	Multiple	Scale	Navigation
	Relative	Traceability Route	Features	Alteration	Features	Calibration	Accuracy
IFSR	Yes	None	Yes	Wear	No	No	Good
IVPS	Yes	None	No	Wear	No	No	Good
NanoCD	Yes	TEM*	No	Unknown	No	No	Good
"Comb"	Yes	TEM	No	Unknown	Yes	Yes	None
SCCDRM	Yes	TEM	No	Corner Rounding	Yes	Yes	Good

Linewidth Results



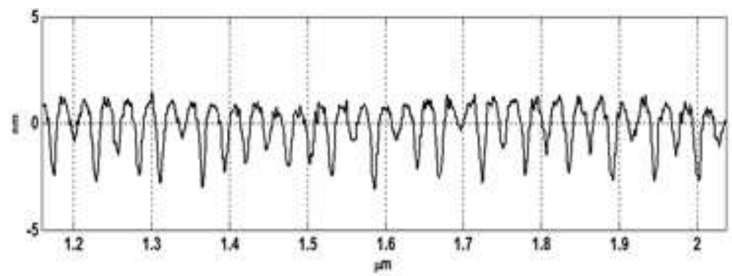
Linewidth values are within 0.5 nm from results based on calibration from other methods.

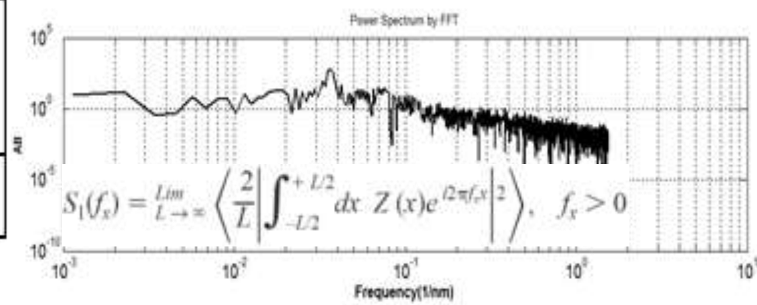
Nanoscale Grating Characterization

Scale Calibration Gratings

- Although the feature widths are known from TEM, if the AFM scale calibration is not correct, the tip widths will be wrong.
- The sample includes gratings that could be used as traceable lateral scale for the whole evaluation process.
- The gratings are calibrated using the NIST T-AFM.

	(nm)	Comment
Mean	28.03	*This is the mean value obtained from the displacement interferometry data.*
Sample Uniformity	0.21	*This is the standard deviation of the grating from a single measurement rather than from repeated measurements, and represents the sample quality.*
1 Standard deviation	0.09	*10 repeated measurements*





Simulation

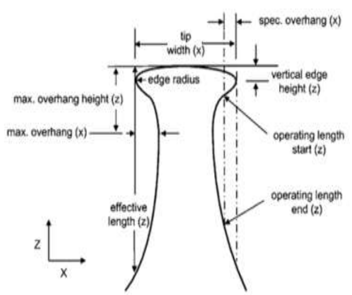
- **When considering using a characterizer, it would be helpful to know if a particular characterizer is suitable for the task.**
- **To do this we simulated the AFM scanning process using a range of tip parameters.**

- **The goal is to**
  - **Be able to specify what types of tips could be used on a specific characterizer. This information will enable users to select appropriate characterizers for their needs.**
  - **Develop a tool for designing specialized characterizers.**

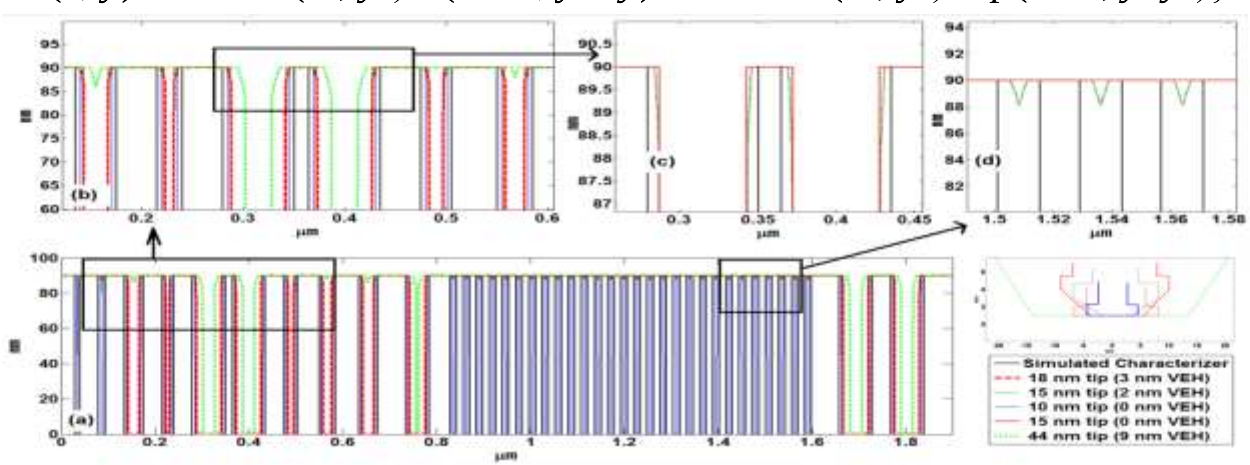
$$A \oplus B = \bigcup_{b \in B} (A + b)$$

$$sim(x, y) = \max\{A(x', y') + B(x-x', y-y')\}$$

$$z(x, y) = \max\{s(x', y') - t(x' - x, y' - y)\} = \max\{s(x', y') + p(x-x', y-y')\}$$



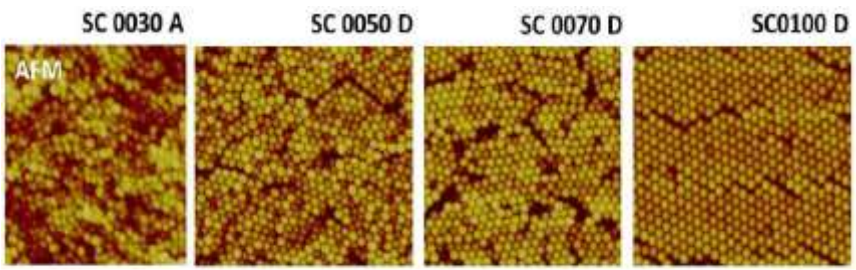
Flared 3D-AFM tip shape parameters



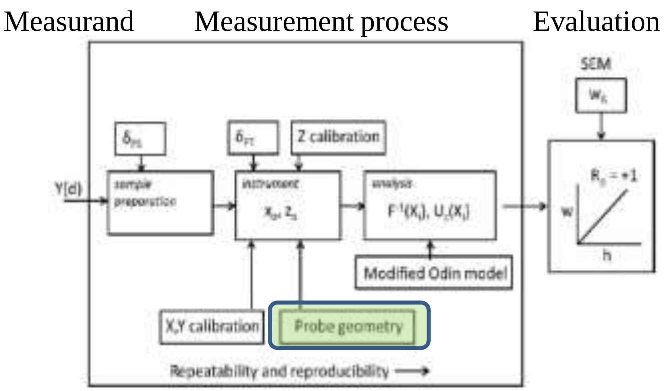
Other Applications

Although our focus has been on semiconductor metrology, probe shape characterization is applicable to a wide range of nano-structures.

John Dagata at NIST used the comb characterizer to evaluate AFM tips for nanoparticle measurements, with a focus on drug delivery systems for nanomedicine. A key part of the work was validating the consistency of individual particle measurements, which requires a detailed knowledge of the probe shape. This was then used to develop models of particle-tip deformation and particle-substrate deformation.



AFM images of different sizes of polystyrene latex reference material used in the study

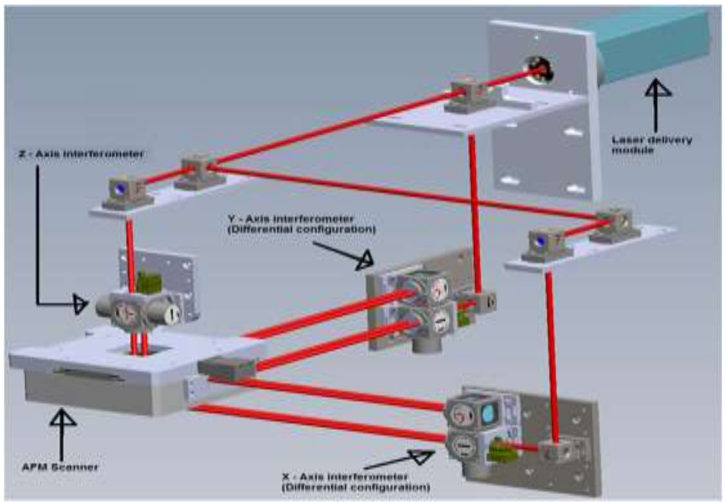


Three manuscripts describing key metrological aspects of this work have been submitted to the journal *Measurement Science and Technology*

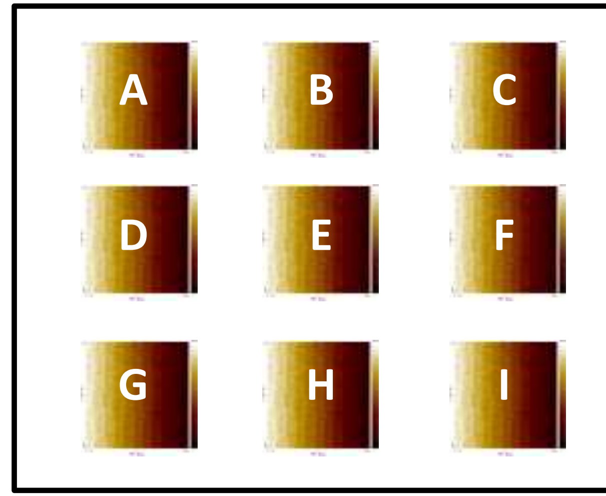
J. A. Dagata et al, Deformation of polystyrene reference spheres in atomic force microscopy

- *I. Use of a tip characterizer for correlated height and width measurements*
- *II. Particle-tip deformation*
- *III. Particle-substrate deformation*

Evaluation of Al_20_3 (Sapphire) Stepped Surfaces



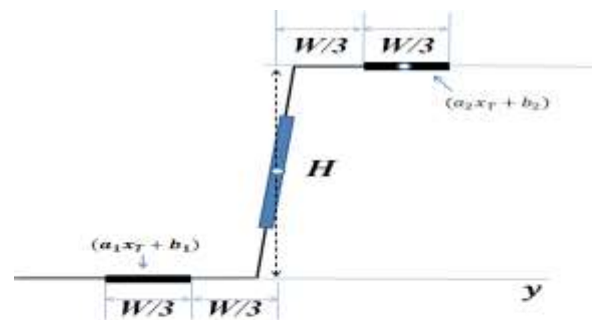
Schematic diagram of T-AFM laser path and stage



Measurement locations on each sample

Analysis Procedure

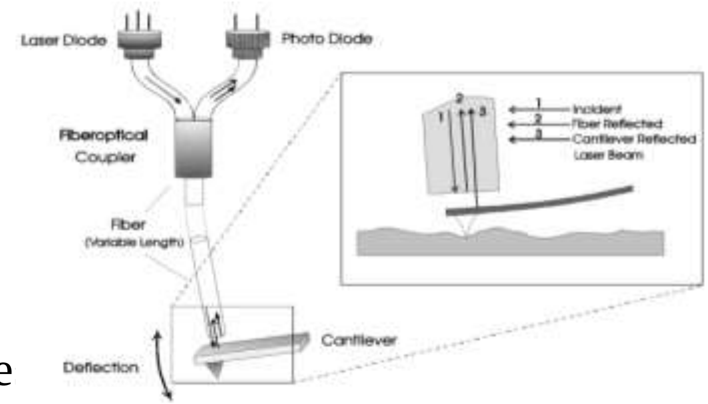
- *One sided step height algorithm*
- *Linear fits to the middle portion of the terraces*
- *The height values fits are extrapolated and determined at the edge.*
- *The step values from each file are averaged.*



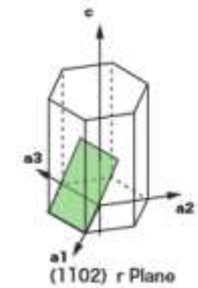
$$H_{meas} = (a_1x_T + b_1) - (a_2x_T + b_2)$$

Instrument: Traceable Atomic Force Microscope

- Metrology AFM with Displacement Interferometry in three axes.
  - ➢ Traceable to the *SI* meter through 633nm He-Ne laser wavelength
- Fiber optic cantilever detection
- Independent x, y, z scanning stage actuators
- Z noise resolution of less than 0.05 nm
- Stage linearity of less than 0.01%
- Abbe offset of less than 5 mm in x and y axe and 0.5 mm in z axis.
- Stage drift of less than 10 nm per hour
- Scan range: 100 µm x 100 µm x 6 µm

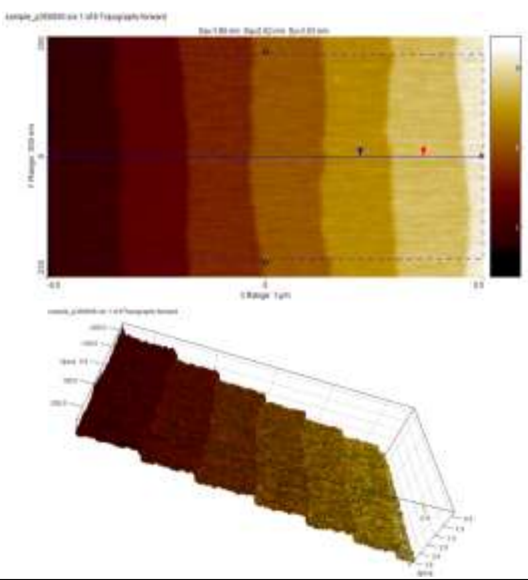


r Plane ($1\bar{1}02$) Nominal Height: 0.35 nm



Qualitative Observations:

- *Well defined edges*
- *Most terraces are more than 150 nm, allowing for adequate area for data fitting.*
- *Relatively low roughness on the terraces.*
- *Short terrace transition region relative to the length of terrace size.*



Location	Mean (nm)	1 SD (nm)
A	0.348	0.008
B	0.359	0.014
C	0.353	0.010
D	0.361	0.008
E	0.357	0.004
F	0.359	0.003
G	0.355	0.008
H	0.356	0.007
I	0.355	0.010
Mean	0.356	0.004

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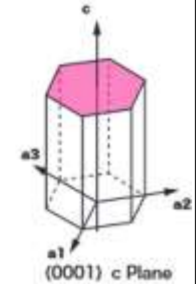
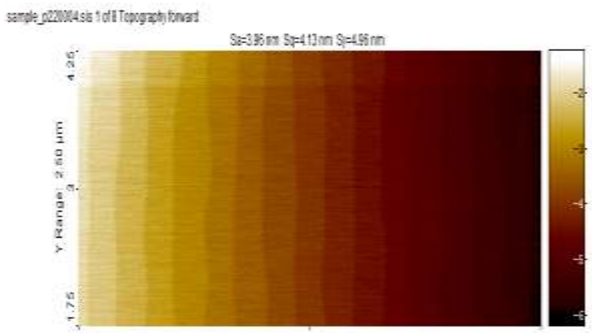
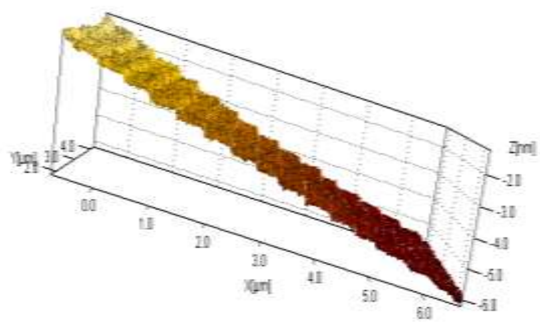
c-Plane (0001) Nominal Height : 0.22 nm



Qualitative Observations:

- *Well defined edges*
- *Most terraces are more than 350 nm, allowing for adequate area for data fitting.*
- *Relative low roughness on the terraces.*
- *Short terrace transition region relative to the length of terrace size.*





Location	Mean (nm)	1 SD (nm)
A	0.220	0.006
B	0.227	0.016
C	0.231	0.012
D	0.230	0.003
E	0.232	0.009
F	0.236	0.005
G	0.218	0.010
H	0.239	0.008
I	0.221	0.008
Mean	0.228	0.007

Summary

- We evaluated the comb characterizer for CD-AFMs and compared the results with existing techniques.
- We report feature size results that are with-in 1 nm compared with existing methods.
- An evaluation of a length standard built into the multi-feature characterizer show an uniformity of less than 0.75 %, indicating that the characterizer could be used as nanoscale *SI* traceable length artifacts.
- We evaluated sub –nm sapphire steps in preparation for ISO standardization and round robin test.

Publications

1. N. G. Orji ; H. Itoh ; C. Wang and Ronald G. Dixson " Technique for AFM tip characterization ", *Proc. SPIE* 9173, Instrumentation, Metrology, and Standards for Nanomanufacturing, Optics, and Semiconductors VIII,

2. N. G. Orji ; H. Itoh ; C. Wang and Ronald G. Dixson “Tip Characterization Method for Critical Dimension Atomic Force Microscopy” Submitted to *Ultramicroscopy*

   J. A. Dagata et al, Deformation of polystyrene reference spheres in atomic force microscopy to be *Measurement Science and Technology*

3. Use of a tip characterizer for correlated height and width measurements
4. Particle-tip deformation
5. Particle-substrate deformation

Continuing Work

- Continue work on different applications of the tip characterizer in semiconductor dimensional measurements.

- Continue collaboration on nano-roughness applications.

- Assist in developing a guideline for round robin test of Al3o2 steps

- Prepare a proposal to set up a study group for scanning probe based techniques for 3D Nanometrology.

  Shape Characterization

  Instrument Calibration and Linearity

Special Thanks To AIST/NMIJ